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Title

A Statistical Approach on End -to-end Proactive Routing Performance in Mobile Ad hoc Networks

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Abstract

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Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols

General Terms

Design, Performance

Keywords

Mobile Ad Hoc Network, Performance, Mobility, Route Duration, Proactive

1. INTRODUCTION

The advent of lightweight devices (such as PDAs) with integrated wireless communication capacities facilitates anytime/anywhere service accessing. Effective and universal service deployment requires supports of increased availability from underlying networks. A mobile ad hoc network [1] comprises a set of nodes connected by wireless link in a temporary manner. The ease of deployment and failure-resilient nature makes MANETs an attractive choice in a variety of applications, such as disaster rescue and battlefields. Such networks are envisioned to have dynamic, sometimes rapidly changing, random, multi-hop topologies, which are likely composed of relatively bandwidth-constrained wireless links. In this context, routing protocols [2] [3] [4] are supposed to provide robust and efficient support (e.g. node detection and route discovery) for service operations.

Unlike fixed networks, the characteristics of MANETs, such as link duration and route duration, vary over time. The transience of local and global network connectivity may significantly affect the performance of MANET routing protocols. For example, node movement results in the disruption of established routes, which directly leads to packet losses and service degradation. Even if each link in an established route is not affected, topology changes in proactive mobile ad hoc networks may still cause route dynamics because of route recalculation and reselection based on SPF (Shortest Path First) algorithm. Moreover, fast topology changes in link state networks lead to inconsistency of routing states between mobile nodes, which generates routing loops, leading to packet drops due to TTL expiration. Therefore, in order to provide guaranteed service in MANETs, it is essential to understand the transience behavior of MANETs and its impact on routing performance under various scenarios and factors, especially for pro-active routing protocols.

There have been several theoretical research efforts on *link dynamics* of mobile ad hoc network. Empirical distributions of link lifetime have been presented in [5] under various simulation parameters. The expected link lifetime of a node is examined under simple mobility scenarios in [6]; it is shown that the expected link lifetime under Brownian motion is infinite, while under deterministic mobility models it can be found explicitly, given the various parameters. Prince et al [7] develops a mathematical model on the statistics of link dynamics, including link life time, new link inter-arrival time, link breakage inter-arrival time and link change inter-arrival time; the study concludes that the link change inter-arrival time density can be modeled by an exponential function.

Analytical studies on route characteristics of mobile ad hoc networks have been limited. Sadagopan et al [8] uses statistical methods to examine the impact of mobility on *path duration* in reactive MANET routing protocols under various mobility models including the Random Waypoint, Reference Point Group Mobility, Freeway and Manhattan model; they discover that, at moderate and high velocities the exponential distribution is a good approximation of the path duration for a range of mobility models.

This paper investigates route dynamics and its impact on pro-active MANET routing performance. An analytical approach is developed to obtain the network statistics of link and path durations including probability density functions (PDFs) and cumulative density functions (CDFs). Further, an analytical model is presented to show the correlation between average route duration and the throughput of pro-active routing protocols. This study aim at gaining a clear insight into the characteristics of *proactive* mobile ad hoc networks under various mobility patterns.

Basically, this study is motivated by the following factors.

First, up till now, there has been no analytical study of route duration distribution in *proactive* MANET routing protocols. Considering the large impacts of mobility on the performance of proactive routing protocols, it is necessary to investigate the route dynamics under various mobility models.

Second, the route dynamics of *proactive* routing protocols are different from those of *reactive* routing protocols because of their routing selection and maintenance mechanisms. The route dynamics in proactive routing protocols are more complex in modeling, because of the optimal route selection algorithms such Dijkstra's Algorithm.

Third, the mobility models used in existing studies may affect the accuracy of analytical results. The commonly used random waypoint model [5] [6] [8] leads to non-uniform spatial node distribution; that is, there is a denser node distribution towards the center of the field than close to the boundaries [9]; the model may generate unreliable results because it fails to present steady state in simulations and the average node speed decays consistently over time [10]. The necessity of using steady-state simulations is discussed further in section 2.4.

The main contributions of this paper is presenting an approach that combines *statistical analysis*, *analytical modeling* and *simulations* in evaluating proactive routing performance and analyzing the correlations between the factors (e.g. velocity and transmission range) and the routing performance.

The rest of the paper is organized as follows. Section 2 lists the related work. Section 3 presents the background knowledge of this study. The experimental methodology including performance metrics, measurement methods and simulation settings is presented in section 4. Observations of the results are shown in section 5. Section 6 gives the analytical model of protocol performance based on the route duration distribution. The conclusions and future work are reached in section 7.

2. RELATED WORK

This study is to investigate the route dynamics of MANET proactive routing protocols under various mobility models. It is inspired by a number of previous works in related MANET research fields.

2.1 Performance Evaluation on MANET Routing Protocols

Up till now, various routing protocols have been proposed in the context of mobile ad hoc networks, which are supposed to provide robust and efficient support for emerging MANET applications. Considering the critical role of the routing protocols, it is necessary (1) to evaluate the merits and drawbacks of each proposed protocol, both qualitatively and quantitatively, and (2) to understand the factors that impact the routing performance, and the correlations, both qualitative and quantitative, between these factors and the performance.

For the first purpose, a lot of experimental efforts have been done, both with simulations and real-world experiments. To evaluate the merits of each protocol, protocol-independent routing metrics have been used, including *throughput*, *traffic overhead* and *end-to-end delay* [11]. Douglas et al [12] presents the *expected transmission count metric* (ETX), which incorporates the effects of link loss ratios, asymmetry in the loss ratios between the two directions of each link, and interference among the successive links of a path, for both proactive and reactive MANET routing protocols.

For the second purpose, there have been several attempts to propose metrics to characterize the network dynamics. Johansson et al proposed the relative motion between mobile nodes to distinguish the different mobility models used for their scenario-based study in [13]. Prince et al [7] derives analytical expressions for a number of link properties, including *expected link lifetime*, *expected link arrival rate*, *expected link breakage rate*, *expected link change rate* and *link change interval time*. Sadagopan et al [8] uses average relative speed to analyze the probability distribution of *link duration* and *path duration* in reactive routing protocols. Two methods are used in measuring such metrics: simulation based statistical approach [8] and modeling based theoretical approach [7].

In addition to the metrics above, this paper studies the *route dynamics*, including the *route duration* and the *route change intervals* as metrics to differentiate different the behaviors of proactive mobile ad hoc networks under various mobility models. The detailed definitions can be found in section 4.1.

2.2 Mobility Models

In order to obtain realistic simulation results, it is necessary to examine the routing performance under multiple mobility models. Generally, various mobility models could be classified into two types, e.g. constrained topology based models and statistical models.

Constrained topology based models simulate real-world scenarios but still have some randomness to provide variability. In our study, we adopt a wide range of constrain topology based models, including freeway model, reference point group mobility model (RPGM), Manhattan model and restricted random waypoint (RRWP) model (part of random trip model [10]). The last two models use real-world maps to generate mobility patterns; for example, RRWP of random trip model use existing American city maps available from TIGER (Topologically Integrated Geographic Encoding and Referencing) database of United States Census Bureau.

Statistical models are featured with full randomness. Nodes can move to any destination with randomly chosen velocities and directions. Although idealistic, this type of models provides common test beds for performance comparison of different routing protocols and also for emerging services in which the nodes' real mobility pattern is not known or foreseeable.

Random waypoint (RWP) model is the most popular statistical model used in previous research. However, recent studies show that RWP has state transience phase and it may take a long time to converge to steady state [9] [10]. In our study, we use the random trip model [10], which provides steady-state simulations (e.g. Perfect Simulations) and removes the need to discard the warm-up period of results.

2.3 Steady-state Simulations

We are commonly interested in measuring the performance of a protocol that is captured by long-run averages. If the node mobility ultimately converges to a steady state, the long-run averages are determined by the mobility steady state.

Camp, Navidi and Bauer [14] point out that if the model has a stationary regime, it is important to simulate it in this regime; otherwise, if the initial configuration is not sampled from the stationary regime, the performance evaluation of a system under study may be biased and non reproducible.

Bettstetter et al [15] studies the time-stationary distribution of a node position for classical random-waypoint model. They observed that the time-stationary node position is non-uniform and it has more mass in the center of a rectangle. A similar problem has been further studied by Bettstetter, Resta, and Santi [16]. A closed-form expression for the time stationary density of a node position is obtained only for random-waypoint on a one-dimensional interval; for two dimensions only approximations are obtained.

Correspondingly, existing results based on Random Way Point simulations and some other models faces several problems such as speed decay. These problems lead to inaccurate analytical results, especially for this study; the node distribution is directly linked with link duration and further with route duration, while the speed setup impacts the node mobility and therefore has a close relationship with route dynamics.

Standard methods for avoiding such a bias include (1) transient removal, e.g. removing the beginning of all simulation runs in the hope that long runs converge to stationary regime, and (2) perfect simulation [10], to sample the initial simulation state from the stationary regime. Yoon, Liu, and Noble [9] find that the non-zero minimum speed setup of the classical random-waypoint helps solve the above speed-decay problem.

3. BACKGROUND

In this section, we present background knowledge on the route dynamics of proactive routing protocols, including routing operations and the differences with reactive routing protocols.

3.1 Routing Operations

In proactive routing protocols, each node maintains a routing table that contains the next-hop information to all reachable destinations; periodical routing messages are broadcasted in order to keep the route tables completely updated at all times. Unlike reactive protocols like AODV [4], proactive routing protocols have no route set up phase and route maintenance phase [8]. Instead, proactive routing protocols use the following two routing operations in presence of mobility.

(1) Neighbor sensing

In this operation, each node detects its neighbor changes, including arrival of new neighbors and leaving of previous neighbor. The basic mechanism used in this operation includes:

(a) Mac layer notification: if a packet fails to be sent, the MAC layer notifies the routing agent about such failure and thus a neighbor loss is detected.

(b) Soft-state mechanism: each node sends periodical heartbeat messages by broadcasting. The node senses a new neighbor once receiving the neighbor's heartbeat message; a lost neighbor is detected if no update messages have been received within a period of time-out intervals.

(2) Propagating neighbor dynamics and synchronizing network state information.

In link-state routing protocols the nodes advertise periodical topology information to the whole network; in distance vector routing protocols, the nodes send the routing tables periodically to its neighbors. Both types of proactive routing protocols follow the same way in route selection in presence of mobility. The route will be re-computed in terms of network dynamics in order to find the shortest path to the destination, even if there is no breakage in each link along the route.

3.2 Differences with Reactive Routing Protocols

The *route dynamics* in proactive routing protocols is more complex, compared with the *path dynamics* in reactive routing protocols.

Besides the basic difference in route discovery, the route maintenance mechanism used in proactive protocols is different from that in reactive routing protocols. In a link-state routing protocol like OLSR, the route between any two nodes may very over time even if each link in the route still exists; it may get stalled because it is no longer the shortest; the route between these two nodes may be re-computed triggered by topology changes; in a reactive routing protocol like AODV, the route between any two nodes will not be changed until any link in current route is broken.

Such a difference leads to different route dynamics behaviors between these two types of MANET routing protocols. Intuitively, the average route duration of proactive routing protocols should be smaller than that of reactive routing protocols; more frequent route changes are expected to be observed in proactive mobile ad hoc networks.

Therefore, it is necessary to investigate the route dynamics of proactive ad hoc networks under various mobility models.

4. EXPERIMENTAL METHOLOGY

In this section, we give the experimental methodology used in this study, including performance metrics and the related measurement methods.

4.1 Performance Metrics

To evaluate the performance of a routing protocol, quantitative metrics need to be defined first. Besides the *independent* metrics, such as link duration and link change arrival interval, we also define the protocol-dependent metrics, namely route duration and the route change arrival interval; these metrics depends on the routing algorithms and have differentiated definitions for proactive and reactive routing protocols.

First, we present the symbols commonly used in this section. Let

(1) n is the total number of nodes in a mobile ad hoc network.

(2) l_{ij} is the length of the shortest route between node i and j.

(3) r_{ij} is the shortest route between node i and node j.

(4) t_0 is the start time of the simulation.

(5) R is the transmission range of a node in the network.

We define the following metrics for our analytic study.

(1) *Link duration*: For two nodes i j, at time t_1, the duration of the link (i, j) is the maximum period [t_1, t_2] during which the two nodes are within the transmission range and there exists symmetric link between the two nodes. Moreover, these two nodes are not connected at time t_1-ε and time t_2+ε for any $\varepsilon > 0$.

(2) *Link Change Interval*: Any change in the set of links of a node may be either due to the arrival of a new link or due to the breakage of an established active link. The link change interval of a node i at time t_1 is the maximum period [t_1, t_2] during which there are no links arrival events or link breakage events; for any ε_1, ε_2 >0 there exist link change events at t_1- ε_1 and t_2+ ε_2.

(3) *Route Duration*: For a shortest route r_{ij} between node i and node j, at time t_1, the route duration is the maximum period [t_1, t_2] during which (a) each of the k-1 links between the nodes is connected and symmetric; (b) the route keeps the shortest between the two nodes. Moreover, at time t_1- ε and time t_2+ ε, $\varepsilon > 0$, either at least one of the k-1 links doesn't exist, or there exists a new route r_{ij}', $l_{ij}' < l_{ij}$.

(4) *Route Change Interval*: Any change in the set of routes may be either due to the breakage of an established active route or due to re-selecting a new route. For nodes i,j, at time t_1, the duration of the route r_{ij} is the maximum period [t_1, t_2] during which there are no route breakage or route re-selection events; for any ε_1, ε_2 >0 there exist route change events at t_1- ε_1 and t_2+ ε_2.

4.2 Probability Density Function and Approximation of Route Distribution

With a large set of samples collected, we use the *relative frequency* approach of the probability theory to estimate the probability density functions (PDFs) of the link and route duration across the different mobility models. Once the PDFs are determined, we calculate the average link duration and the average route duration based on the probability.

In order to approximate the distribution, we use the standard *curving fitting* technique to analyze the PDFs of the link and route duration across the different mobility models; the results of the curve fitting including RMSE etc are listed in tables to facilitate further analysis.

With the fitting data with one or more models, it is necessary to evaluate the *goodness of fit*. Goodness of fit here means how well a statistical model fits a set of observations. Measures of goodness-of-fit typically summarize the discrepancy between observed values and the values expected under the model in question. Besides the visual examination of the fitted curve displayed, we use numerical measures including *SSE*, *R-square*, *Adjusted R-square* and *RMSE* to assess the goodness of fits and help determine the best fit.

The sum of squares due to error (*SSE*) statistic is the least squares error of the fit, with a value closer to zero indicating a better fit.

The *R-square* is the square of the correlation between the response values and the predicted response value, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the model.

The *adjusted R-square* statistic is generally the best indicator of the fit quality when you add additional coefficients to the models.

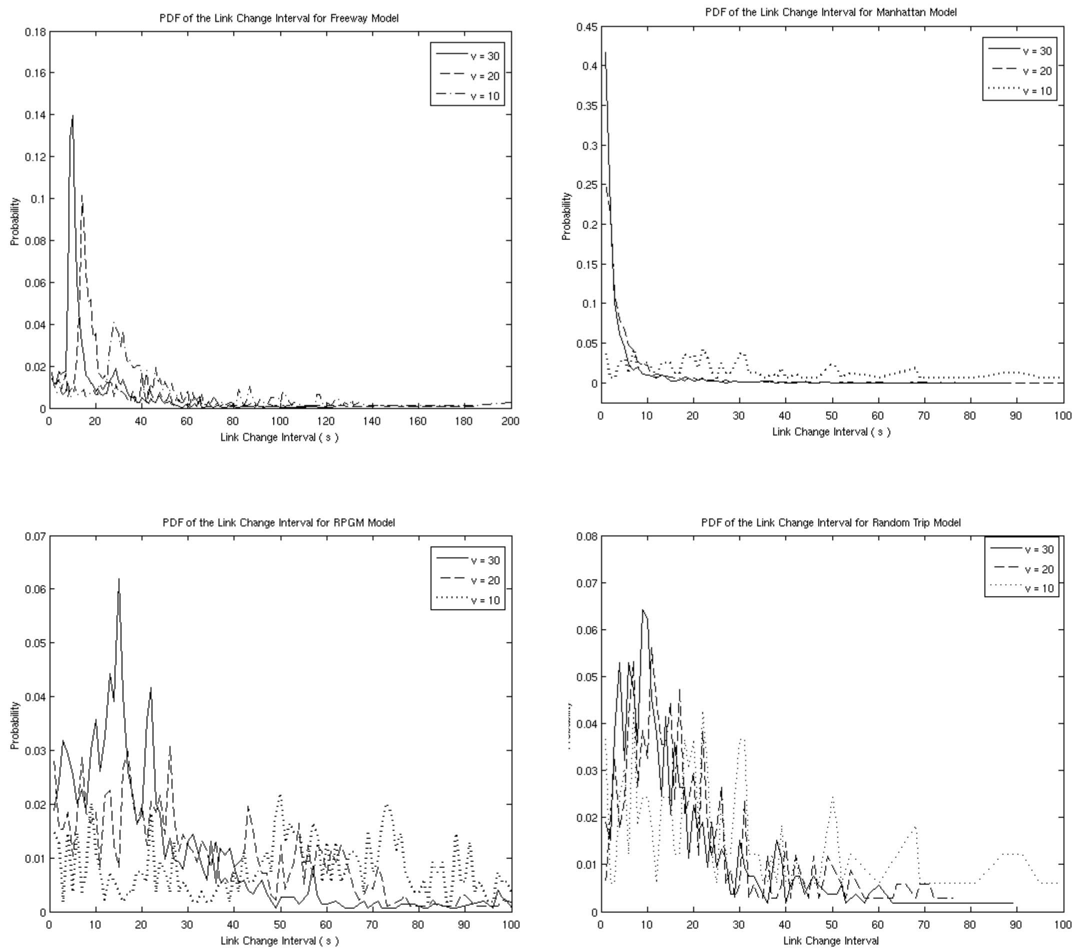
Root Mean Squared Error (*RMSE*) measures the fit standard error, with a value closer to zero indicating a good fitting.

4.3 Simulation Setup

The simulation study is conducted with the OLSR implementation from [19] which runs in version 2.9 of NS2 [20] and uses the ad-hoc networking extensions provided by CMU [21], with the use of MAC/802_11 as the media access control. The radio range is set to 50m, 100m, 150m, 200m, 250m, 300m and 400m separately.

We use a network consisting of n nodes: n = 20 to simulate a low-density network, n = 50 to simulate a high-density network. The nodes are randomly placed in an area of 1000m by 1000m. All simulations run for 900s.

In order to gain good confidence in the measurement results, we run the simulations 100 times for each data point to obtain the mean value, with different mobility pattern file, i.e. a different starting state for the node positions.



We use the Random Trip Mobility Model [10], RPGM (Reference Point Group Model), Freeway Model and Manhattan Model. The maximum speed is set to 1, 5, 10,20,30,40,50 and 60 m/s for each mobility model, while the minimum speed is set to non-zero, e.g. 1m/s for our cases. The mobility patterns Freeway RPGM and Manhattan are generated by [22]; the mobility patterns Random Trip are generated by [23]. RPGM model has 4 groups, with speed deviation ratio set to be 10% of the maximum speed.

5. OBSERVATIONS & DISCUSSIONS

In this section, we present the observations on the network dynamics under various mobility models.

5.1 Dynamics of Link Duration

The distribution of link change interval under various mobility models is non-exponential, contrary to [7], no matter whether the maximum velocity is small or large. Further, the following phenomena have been observed from *Fig 1*.

For the PDF of the link change interval for Freeway model,

(1) When the node speed is relatively low (i.e. smaller than 10 m/s), the probability density has smaller fluctuations; that is, the value of the link change intervals is relatively evenly distributed in the range of $[0,T]$ (T is the simulation sampling period).

(2) When the node speed is relatively high (i.e. larger than 10 m/s), there are peaks in the probability density curves which center in the area of small link change intervals; this indicates that, in high-mobility networks, small link change intervals occupy a larger proportion of the whole link change interval space.

(3) With the increase of node maximum speed, the peak of the probability density moves towards the left side, and the value of the peak probability gets larger, which means the (average) link change interval get smaller; that is, with the increase of network mobility, the link change rate gets bigger.

The similar phenomenon is also observed in other three models. Only in Manhattan model at high mobility, the probability density function shows similarity with exponential distribution. The distribution under other three models doesn't.

Further, the relationship between *average link duration* and the factors (i.e. velocity and radio range) is observed as follows.

From *Fig 2* and *Fig 3* we can see that,

(1) The average link duration increases with transmission range *R* while decreasing with node velocity *V*. The larger the velocity is, the better linear relationship is observed between average link duration and radio range.

(2) The impact of the transmission range on link duration decreases with the increase of node velocity. From Fig 3, for Freeway models, when *Vmax* is smaller than 10m/s, there is a large increase in average link duration when the radio range is increased from 50m to 400m; however, when *Vmax* exceeds 20 m/s, the improvement on average link duration is much less. A similar phenomenon is also observed in other three models. Correspondingly the impact of the transmission range on average link duration in low mobility networks is much larger than that in high mobility networks.

The phenomenon described above is observed in all of the mobility models used in this study, including Random Trip model, Freeway Model, RPGM Model and Manhattan Model.

5.2 Dynamics of Route Duration

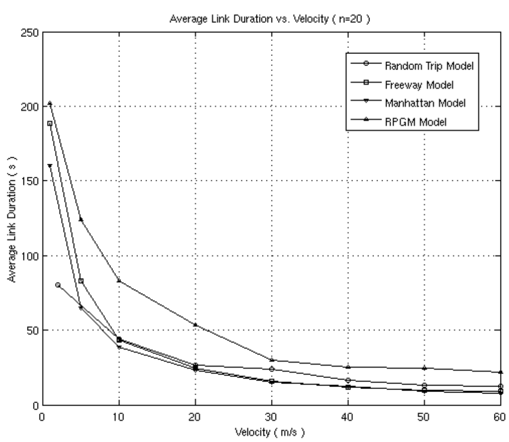
From the distribution of route duration (*Fig 4*) and the curve fitting results (*Table 1*) we can see that, under Random Trip model,

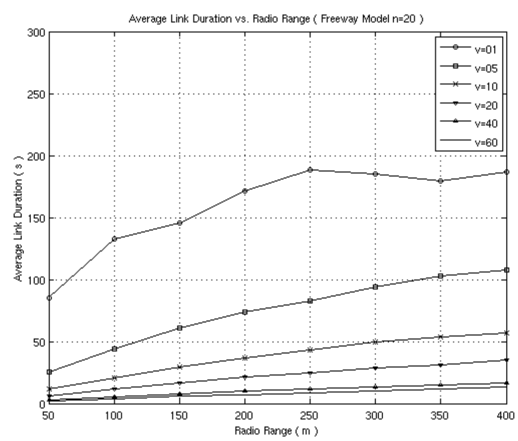
(1) When the velocity is relatively small (i.e. *v* is smaller than 5m/s), the route duration distribution is non-exponential.

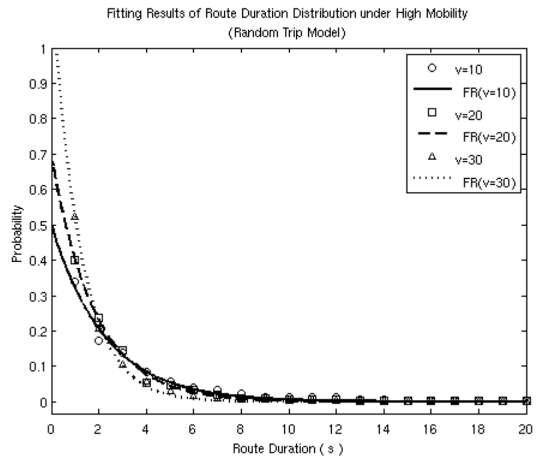
(2) With the higher network mobility (i.e. *Vmax* larger than 10 m/s), the route duration could be approximated by exponential distribution with 95% confidence and satisfactory goodness of fit (*SSE* < 0.003, *R-square*> 0.99, *RMSE*<0.008).

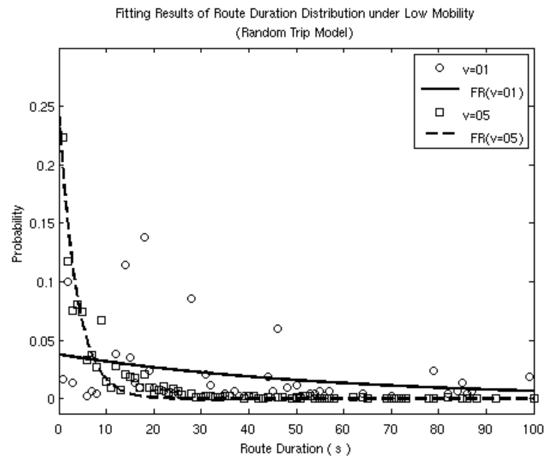
The phenomenon above has been observed under all of the mobility models used in this study.

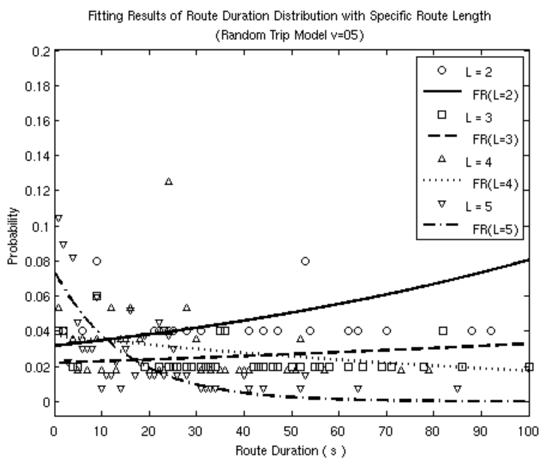
Note that, the observation above is on the route duration sets with *varied route lengths*. The route duration of specific route lengths is shown in *Fig 5*, *Fig6*, *Table 2* and *Table 3*.











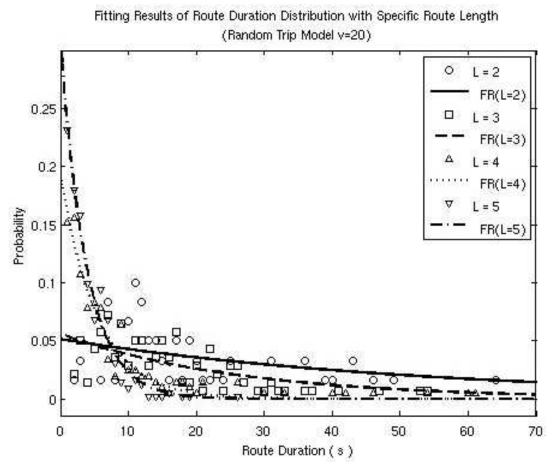


Table 1. Goodness of Fit (Fig 4)

	SSE	R-square	Adjusted R-square	RMSE
FR (v=1)	0.04419	0.0513	0.03022	0.03134
FR (v=5)	0.00742	0.9059	0.9045	0.01045
FR (v=10)	0.002215	0.9862	0.986	0.006234
FR (v=20)	0.0008506	0.9962	0.9961	0.0043
FR (v=30)	0.001036	0.9966	0.9965	0.005155

Table 2. Goodness of Fit (Fig 5)

	SSE	R-square	Adjusted R-square	RMSE
FR (L=2)	0.01283	0.173	0.1424	0.0218
FR (L=3)	0.007502	0.4655	0.4503	0.01464
FR (L=4)	0.003384	0.9367	0.9345	0.01099
FR (L=5)	0.002497	0.9715	0.9698	0.01212

Table 3. Goodness of Fit (Fig 6)

	SSE	R-square	Adjusted R-square	RMSE
FR (L=2)	0.01276	0.1823	0.1369	0.02662
FR (L=3)	0.00869	0.02184	-0.005327	0.01554
FR (L=4)	0.01363	0.04934	0.01867	0.02097
FR (L=5)	0.01052	0.5048	0.4911	0.01709

From the route duration of certain route lengths (*Fig5* & *Fig6*) we can see that, under Random Trip Model

(1) At relatively high mobility, route duration of short routes (i.e. the route length is smaller than 4) is non-exponentially distributed, while route duration distribution of longer route (i.e. the route length is larger than 4) can be approximated with exponential distribution.

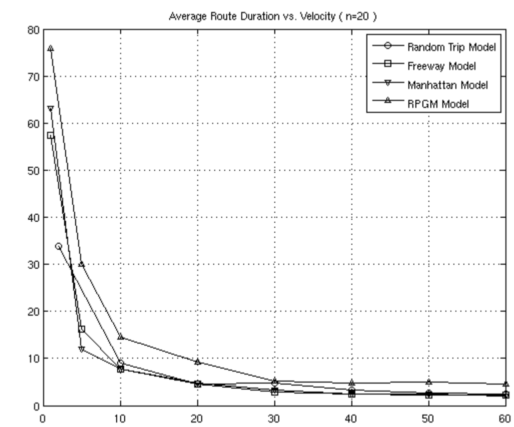
(2) At low mobility, route duration with specific route lengths is non-exponential.

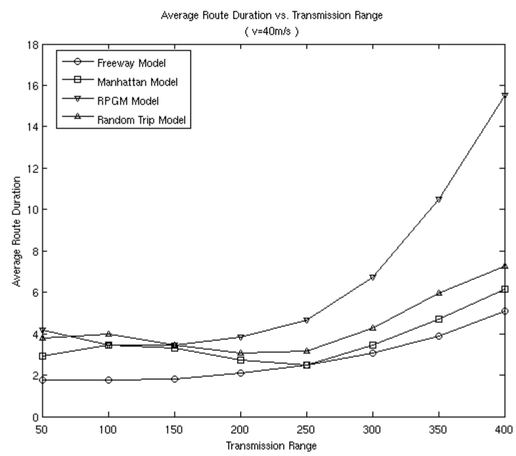
Such phenomena have also been observed under other mobility models including Freeway, Manhattan and RPGM.

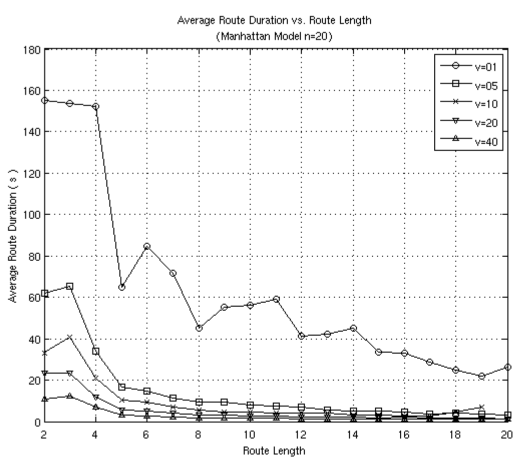
Further, from the results on *average route duration* (*Fig 7*), we can see that,

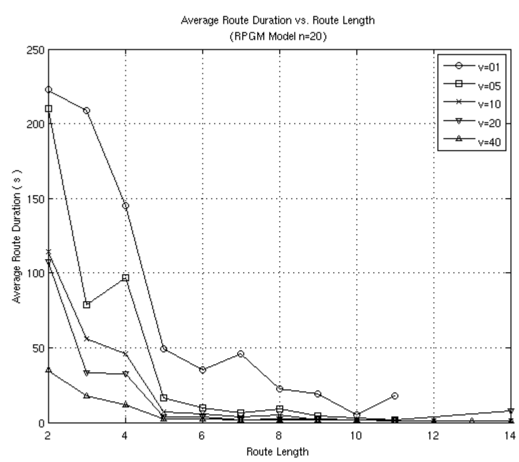
(1) The increase of node mobility leads to the decrease of average route duration; more specifically, the average route duration is inversely proportional to the maximum velocity. Such a relationship is observed under various mobility models.

(2) Generally speaking, the greater the length of the route is, the more likely a route is to break. From (c) (d) of *Fig 7*, the trends of the curves show longer routes have smaller route duration averagely. For example, under various mobility models, the average route duration of 2-hop routes is larger than that of 6 (or more) hop routes. However, the relationship is not inversely proportional since the curve of average route duration is not smooth; in some cases the shortest routes have smaller average duration. For example, under Manhattan model, the average duration of 2-hop routes is smaller than that of 3-hop routes, while under RPGM model, the average duration of 3-hop routes is not (significantly) larger, in some cases even smaller









than that of 4-hop routes.

(3) Intuitively, as the transmission range R increases, the link duration is increased and hence the average route duration is expected to increase. From (b) of *Fig 7*, under various mobility models, when the nodes' maximum speed is relatively high (i.e. v is larger than 10m/s), the increase of node transmission range leads to the increase of average route duration; more specifically, the average route duration is almost proportional to the transmission range when the transmission range is larger than 250m.

6. MODELING ROUTE DURATION OF PROACTIVE MANET

In this section, we present the applications of the statistical study on the link and route duration across a range of mobility models. We first propose an analytical model for the route duration distribution based on the discussion in section 5. With the model we investigate the quantitative relationship between the throughput and the factors such as velocity and transmission range. The analytical model and the quantitative relationship are further validated by results from simulations.

Without losing generality, we assume

(1) The data traffic is CBR traffic, e.g. the traffic rate in each data flow is constant; even if the actual data traffic rate varies over time, the rates within a small Δt could be thought as constant rate.

(2) The transmission range of the nodes is identical in the network; even if the nodes within a network have different transmission range, the nodes with similar transmission range in a small area could be approximately identical.

6.1 Analytical Model for Route Duration Distribution

Based on the results of statistical study on link and route duration distribution, we assume that in a mobile ad hoc network with moderate or high mobility, the route duration under various mobility models is exponentially distributed. The parameter λ for this exponential distribution, i.e. the reciprocal of the expected route duration, is determined by the following factors:

(1) *Node velocity v*. Intuitively the increase of the nodes' mobility leads to the decrease of link duration since the link is more likely to get broken. Hence, $\lambda \propto v$.

(2) *Transmission range R*. As the transmission range increases, link duration increases, and the route duration increases. Hence, $\lambda \propto 1/R$.

Therefore,

$$\lambda = \frac{\lambda_0 V}{R}$$

Note that, the exponential characteristic is shown in the route set with variant route length; according to the study in section 5, only the route duration distribution of long route (L >=4) could be approximated by exponential distribution. Therefore, route length is not included as one of the factors of the duration distribution.

The above model has been verified initially by the previous analysis on average route duration. As shown in *Fig 7*, at moderate or high mobility, the average route duration is inversely proportional to the velocity while proportional to the transmission range.

Thus, the distribution of the route duration across various mobility models, under moderate or high mobility, can be approximated by the following exponential distribution.

$$f_d(x) = \frac{\lambda_0 V}{R} e^{\frac{-\lambda_0 V}{R} x}$$

The cumulative density function of the route duration under various mobility models can be approximated by:

$$F_d(x) = 1 - e^{\frac{-\lambda_0 V}{R} x}$$

6.2 Throughput Analysis Based on The Route Duration Distribution Model

Let

(1) T is the length of the simulation.

(2) $d_{i,j,k}$ is the kth route duration of node i and node j; { $d_{i,j,0}$, $d_{i,j,1}$, …, $d_{i,j,k}$,… } is the link duration set of node i and node j during the simulation.

(3) D is the total data transferred during the simulation.

(4) $D_{i,j}$ is the data transferred between node i and node j during the simulation.

(5) $D_{i,j,k}$ is the data transferred between node i and node j during the route duration $d_{i,j,k}$.

(6) r is the data rate transferred across the network, which is assumed to be constant in this study.

(7) n is the number of the data flows in the simulation.

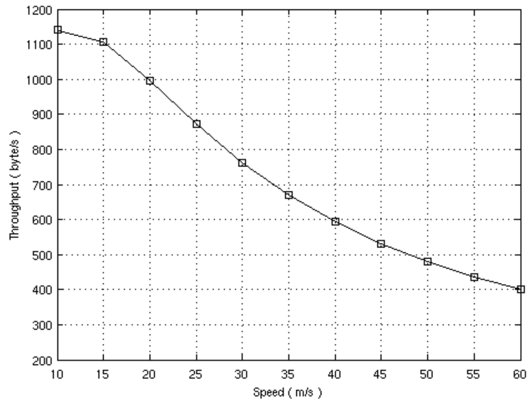
(8) l is the average number of route segments in end-to-end connection.

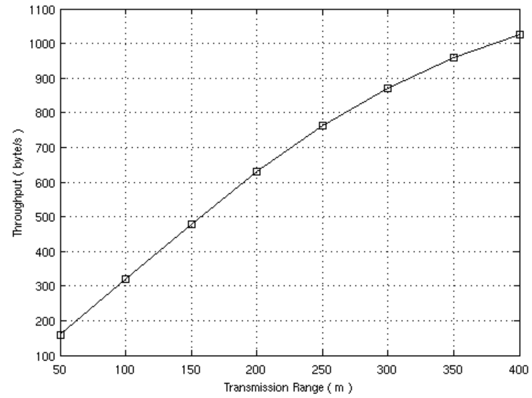
(9) f_d is the PDF of the route duration distribution.

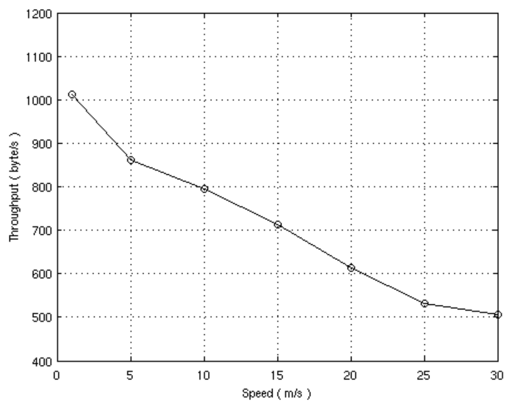
The throughput of a network is calculated by averaging the throughputs of each data flow. Without losing any generality, we assume the length of each data flow is the same with the simulation time T. Therefore, the throughput is

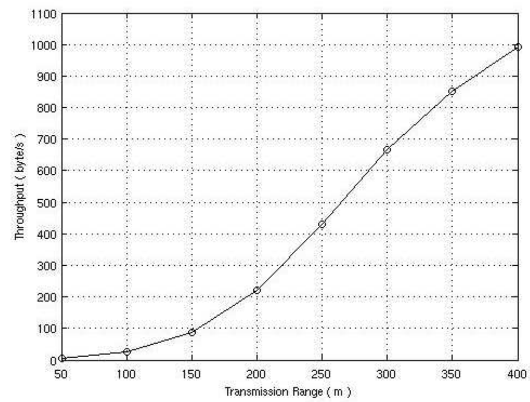
$$Throughput = \frac{\sum_{i,j} \frac{D_{i,j}}{T}}{n} = \frac{\sum_{i,j} D_{i,j}}{nT} = \frac{D}{nT}$$

The throughput analysis is as follows.









$$
\begin{aligned}
Throughput &= \frac{D}{nT} \\
&= \frac{\sum_{i,j} D_{i,j}}{nT} \\
&= \frac{\sum_{i,j}\sum_{k} D_{i,j,k}}{nT} \\
&= \frac{\sum_{i,j}\sum_{k} r \times d_{i,j,k}}{nT} \\
&= \frac{r\sum_{i,j,k} d_{i,j,k}}{nT} \\
&\doteq \frac{rl\int_{T} f_{d}(t)tdt}{T} \\
&= \frac{rl\int_{T} \frac{\lambda_0 V}{R} e^{\frac{-\lambda_0 V}{R}t} tdt}{T} \\
&= \frac{rlR}{\lambda' V} - \frac{rlR}{\lambda' V} e^{\frac{-\lambda' V}{R}} - rle^{\frac{-\lambda' V}{R}}
\end{aligned}
$$

By assigning values to the parameters of the above throughput equation, we obtain the analytical relationship of (1) throughput and velocity and (2) throughput and transmission range, as shown in Fig 8.

In addition, we validate the above throughput model by the simulations. The setup of the simulations is the same as described in section 4.3. The simulation results are shown in Fig 9.

As shown in above results, the average throughput of pro-active routing protocols is nearly proportional to transmission ranges while inversely proportional to velocity.

7. CONCLUSIONS AND FUTURE WORK

This paper investigates the impact of mobility on proactive MANET routing protocols. A statistical approach is developed to obtain the network statistics of link and path durations including probability density functions (PDFs) and cumulative density functions (CDFs). Further, an analytical model is presented to show the correlation between average route duration and the throughput of pro-active routing protocols; the analytical results have been further validated with NS2 based simulations.

This paper shows that, at moderate or high mobility, the distribution of route duration of pro-active mobile ad hoc networks can be approximated by exponential distribution. The analytical model on throughput shows the proportional relationship between throughput and node transmission and the inversely proportional relationship between throughput and node mobility velocity.

This study is under multiple assumptions on transmission range and traffic patterns. Therefore, the models are derived from simplified scenarios. In the following studies, it is interesting to investigate richer analytical models to analyze the quantitative relationship between other performance metrics (such as overhead) and extra factors (such as node density). A comprehensive study on the impacts of various factors on mobile routing performance will lay a solid theoretical foundation for designing new MANET protocols and MANET applications.

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